VISUALIZATION OF ELEVATION MODELS AND REMOTE SENSING IMAGERY FOR TECTONIC ANALYSIS

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ABSTRACT

The Shuttle Radar Topography Mission is generating digital elevation models (DEMs) at 30 meters resolution and satellites such as Ikonos now acquire one-meter resolution imagery. Together, these data sets will provide our first detailed comprehensive look at landforms across most of the Earth's surface. Stereoscopic combinations of the DEMs and imagery, particularly in tectonically active rugged terrain, are perceived to be nearly equivalent to aerial photographic stereo pairs at the imagery's higher resolution. Advantageously, and unlike aerial photography, these data sets have little radial distortion, can be manipulated to show any vertical exaggeration, and will be immediately accessible. In these views, fault traces and their offsets can be seen and measured based upon their full three-dimensional geomorphic expression. When further combined with Landsat or other multispectral imagery, fault traces and offsets are revealed by their displacement of spectrally differentiable lithology. Thus, six perceptual dimensions (three-dimensional shape plus three-dimensional color space), derived from three complementary data sets, can be combined into very powerful terrain analysis tools. These data sets and tools have immediate use in seismic site evaluations and will substantially improve global tectonic maps.

Introduction

Geomorphic analyses are a critical part of seismic hazard evaluation. Although individual earthquakes typically produce only minor changes to local topography, their effects are often "characteristic" (similar and repetitive) and are therefore amplified over time, resulting in distinctive landforms that reflect their causative tectonic processes. New satellite data sets and developing methodologies are now facilitating analysis of these landforms at high resolution. Capabilities to map lithologies by their spectral reflectance and emission properties are also improving. This paper illustrates the characteristics of some of the new global data sets and demonstrates that synthetic stereoscopic mergers of satellite imagery and digital elevation models (DEMs) can synergistically produce highly effective landscape analysis tools for tectonics research.

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Global Image Data Sets

Several global image data sets useful for recognition of tectonic landforms are now available and several others are expected soon. The first such data set was Landsat-1, launched in 1972. It viewed the Earth at 80m spatial resolution in the green, red, and near-infrared wavelengths. This first good view of the Earth's crust from space helped improve tectonic maps at global and continental scales, but was not very useful for local studies nor did it provide much capability to map lithologies based upon their spectral properties. Landsat-4, launched in 1982, improved the spatial resolution to 30m and broadened the spectral range enough so that three or more lithologic variables (e.g. ferric iron, ferrous iron, carbonates, and hydroxyls) could be mapped, thus filling three-dimensional color space in a well enhanced image (e.g. Fig. 1). In 1986, the first French SPOT satellite was launched and provided black-and-white imagery with 10m resolution. Many researchers found ways to merge the SPOT image detail with the Landsat spectral information into a single display. Also, SPOT provided stereoscopic capabilities (unlike Landsat). Since 1995, the Indian IRS-1 satellites have provided image detail approaching 5m, but like SPOT have not improved upon Landsat's spectral capabilities. Meanwhile, in addition to these optical systems, radar imaging satellites also began producing global image data sets with resolutions of about 25m, including the European ERS (1991), the Japanese JERS (1992), and the Canadian Radarsat (1995). Interferometric processing of radar data sets now facilitates the mapping of seismic strain at centimeter precision in unprecedented spatial detail.

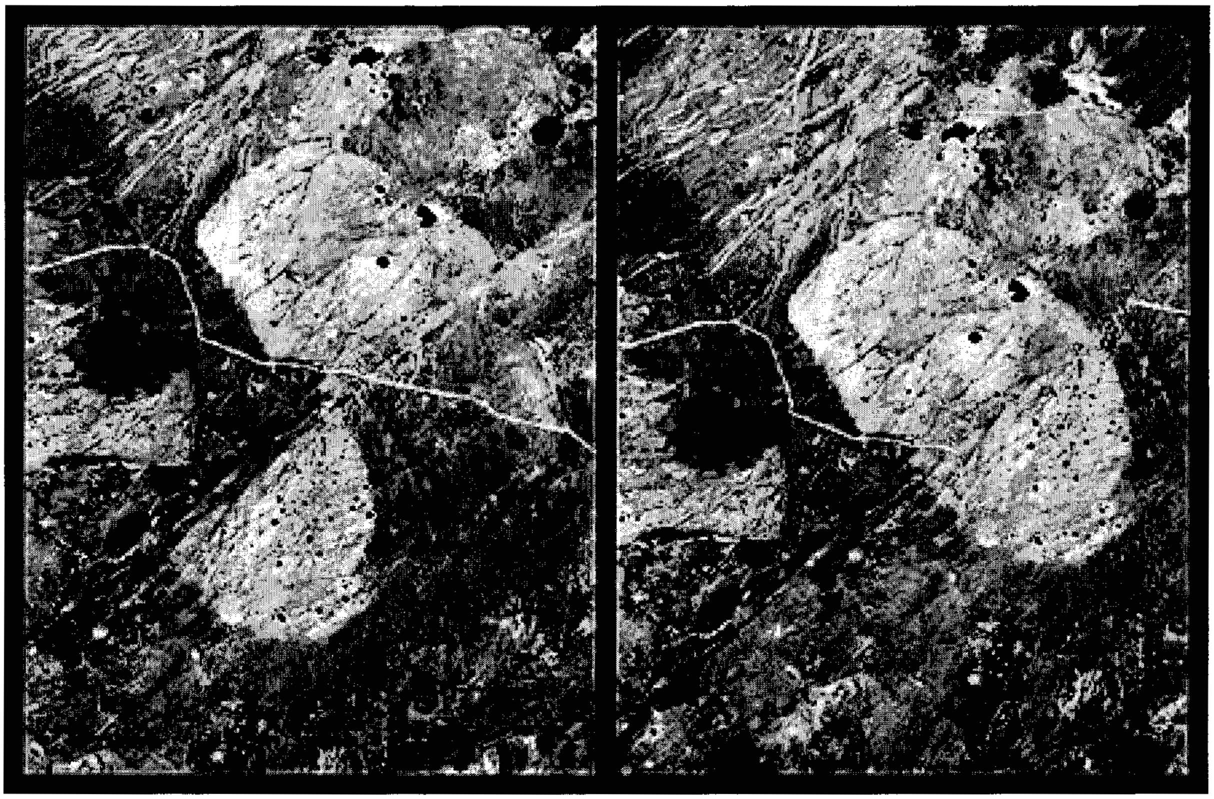


Figure 1. Enhanced Landsat-7 image of terrain near Los Menucos, Argentina. Left: Natural scene. Right: Fault offset graphically removed (3.3 km) to rejoin halves of an igneous intrusion.

Recent and imminent imaging satellite launches include (1) Ikonos, a commercial 1m optical imager, launched in 1999, (2) other high resolution imagers such as OrbView, due in 2000, (3) Landsat-7, which is similar to earlier Landsats but with an added 15m black-and-white imager (launched in 1999), and (4) ASTER, part of the international Earth Observation System launched in early 2000. ASTER imagery should prove highly useful for lithologic mapping given its several spectral channels in the reflectance and thermal infrared spectral regions. However, the spatial detail of Ikonos and other high resolution imagers will be essential in detailed fault zone studies.

Figure 2 compares a SPOT 10m image to a simulated Ikonos 1m image for fault breakage along the Emerson fault resulting from the 1992 Landers, California earthquake. (Aerial photography is used for the simulated Ikonos image.) Note that although the fault break can be seen locally at 10m, details of the break are vastly clearer at 1m. Note too that image patterns, such as the vegetation pattern, seen at 1m are lost (becoming flat grey) at 10m. Such patterns are needed to comprehensively measure tectonic terrain displacements in optical imagery.

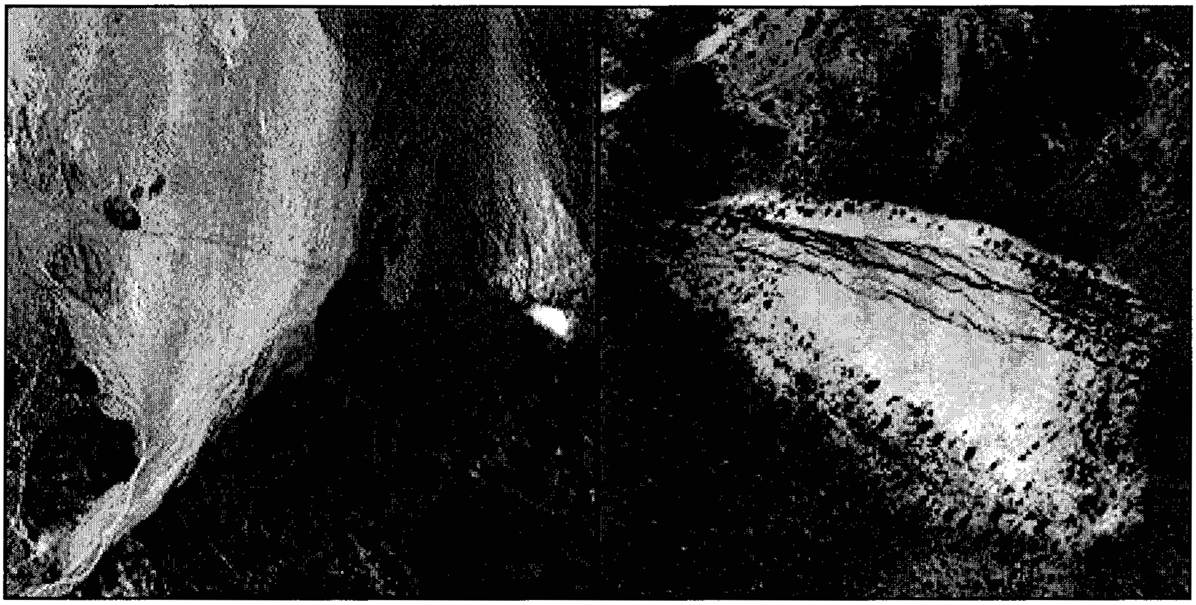


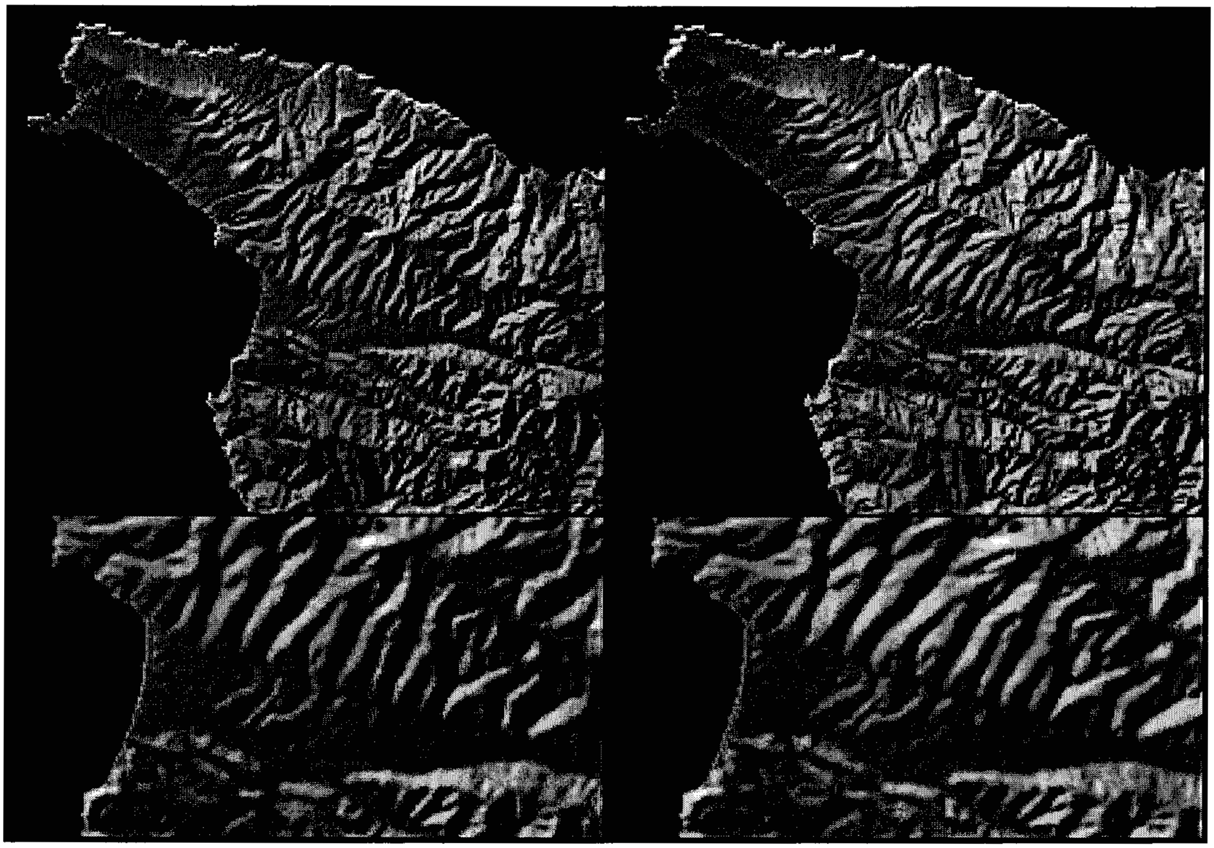
Figure 2. Emerson fault, Mojave Desert, after the Landers earthquake. Left: SPOT 10m image showing fault break in alluvium with playa at right. Right: Simulated Ikonos 1m image of playa.

As one can infer from Figure 2, newly available high resolution images such as Ikonos allow satellite imaging to approach (and in some ways exceed) the utility of aerial photography. Advantageously, they are globally and rapidly available, they have much less radial distortion that aerial photography (in nadir views), and they can be readily merged with other digital geospatial data sets.

Global Topography Data Set: SRTM

In February 2000, the Shuttle Radar Topography Mission (SRTM) was flown aboard the Space Shuttle Endeavor. SRTM is a NASA/JPL mission, funded by the National Imagery and Mapping Agency (NIMA), designed to produce a 30m digital elevation model (DEM) of the world from 60 degrees north latitude to 56 degrees south latitude (all of the world's landmass except Antarctica, most of Alaska, northern Canada, Scandinavia, northern Russia, and northern Siberia). Production of the dataset is expected to take two years.

DEMs at 30m resolution are adequate to observe many tectonic features, including some offset features. Figure 3 is a DEM of the Santa Cruz Island fault, California, shown in stereoscopic shaded relief (discussed below). Note that left-lateral offsets are clearly evident.



Right-Eye Images Left-Eye Images

Figure 3. Cross-eyed stereo pairs, USGS 30m DEM of Santa Cruz Island, California (lower pair is 2X enlargement). Fault trace is distinct and shows left lateral offsets of up to 300 meters.

By itself, the SRTM DEM could facilitate a revolution in global tectonic mapping similar to that facilitated by the Landsat satellites over the last three decades. However, when SRTM data are combined with the wealth of satellite imagery now and soon to be available, remote tectonic mapping methods will be far more powerful. The remainder of this paper discusses and further demonstrates synthetic stereoscopy, which is not only an ideal tool for analyzing DEMs (as seen in Fig. 3), but which can also be used to create highly beneficial perceptual mergers of satellite imagery and DEMs.

Synthetic Stereoscopy

Stereoscopic visualizations of elevation models can reveal the complete geomorphic character of a region at the scale of the DEM, resulting in new discoveries of tectomorphic signatures sometimes even in areas that have been substantially studied in the field. Such visualizations are powerful analytical tools. Nadir-viewing stereograms, having controllable vertical exaggeration, reveal every aspect of terrain morphology (relative slope, relative elevation, slope aspect, landform alignments, drainage deflections, etc) for every pixel simultaneously over wide areas in a form that is readily comprehensible by the human perceptual system.

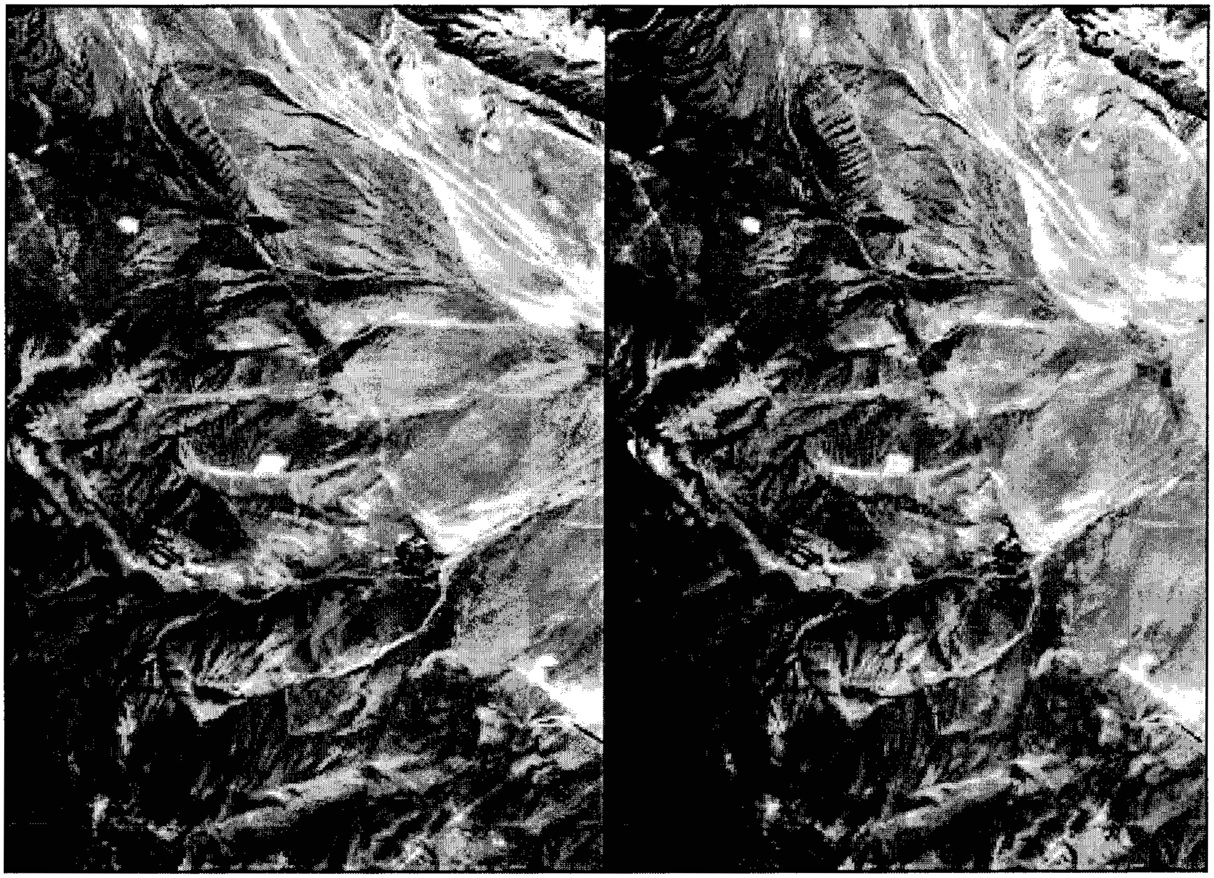
Creating synthetic stereo pairs is fairy easy. Parallax is created by generating two symmetrically off-nadir perspective views. In simple terms, the pixels are shifted as a function of elevation, left for the right eye and right for the left eye. All processing occurs on one image line at a time, so computer memory requirements are minimal and almost independent of image size. However, the algorithm becomes more complex than the basic concept because moving pixels left and right compresses and stretches the image, putting two pixels in some locations and leaving none in others. Also, moving pixels in full pixel steps introduces quantization into the synthesized parallax, resulting in the possibility of perceptible stair steps in the stereoscopically viewed terrain. To avoid these problems, the shifting procedure needs to (1) proportionally spread an input pixel over two output pixels based on its new subpixel position, and (2) fill any empty output pixels by along-line interpolation. When these extra steps are taken, the result is a perfectly natural appearing stereo image pair.

Image-DEM Synergism in the Recognition of Geomorphic Features

Individually, satellite imagery and digital elevation models have several benefits. Satellite imagery is available worldwide with few (if any) political or economic access problems, and it has now reached spatial resolutions similar to aerial photography but with repetitive and timely coverage. Meanwhile, DEMs purely define the form of the land, and synthetic shading of them allows visualizations not attainable with natural lighting, atmospheric conditions, and viewpoints.

However, mergers of satellite imagery and DEMs go a step further. The characteristics of the data sets are complementary in ways that are easily and simultaneously perceived by the human visual system. Indeed, incorporation of satellite imagery into synthetic stereoscopic views creates a synergistic effect. The image is better understood by adding depth as a new and independent perceptual dimension, such that topographic control of image patterns becomes apparent and unambiguous. Likewise, the DEM landforms are better understood as their textures and patterns are found to relate to lithologic differences apparent in the image.

Very importantly, the ability to control vertical exaggeration in synthetic stereograms can greatly enhance the perception of low relief landforms. Such control is not possible with natural stereo pairs (e.g. aerial photography). Note how stereoscopic viewing of Figure 4 greatly clarifies image patterns that are somewhat ambiguous when viewed monoscopically. The extreme vertical exaggeration helps reveal interactions of the tectonic structures and the fluvial systems.



Right-Eye Image Left-Eye Image

Figure 4. Cross-eyed stereo pair (SPOT image and USGS DEM) of the Calico fault and other faults in alluvium northwest of Twentynine Palms, California, with extreme vertical exaggeration.

Conclusion

New satellite images and elevation models provide effective tools for both local seismic assessments and global tectonic mapping. At resolutions as fine as one meter, satellite images show fault zones in substantial detail. At 30 meters resolution, the SRTM global elevation model will greatly improve our knowledge of the world's landforms, especially when perceptually merged with imagery. These data sets, and supportive technologies, facilitate great new possibilities in desktop analyses of seismogenic terrains.